Tomorrow optical interferometry: astrophysical prospects and instrumental issues

Fabien Malbet

Laboratoire d'Astrophysique de Grenoble
CNRS / Université Joseph Fourier (Grenoble 1)
BP 53, F-38041 Grenoble cedex 9, France

Fabien.Malbet@obs.ujf-grenoble.fr

ABSTRACT. *Interferometry has brought many new constraints in optical astronomy in the recent years. A major leap in this field is the opening of large interferometric facilities like the Very Large Telescope Interferometer and the Keck Interferometer to the astronomical community. Planning for the future is both easy –most specialists know in which directions to develop interferometry– and difficult because of the increasing complexity of the technique. I present a short status of interferometry today. Then I detail the possible astrophysical prospects. Finally I address some important instrumental issues that are decisive for the future of interferometry.*

RÉSUMÉ. *L'interférométrie a permis d'apporter de nouvelles contraintes en astronomie optique dans les dernières années. Dans ce domaine, l'ouverture d'interféromètres à très grandes ouvertures comme ceux du Very Large Telescope européen ou du télescope Keck américain a permis d'effectuer un énorme bond en avant. Penser le développement futur est à la fois facile –la plupart des spécialistes savent dans quelles directions se diriger pour développer l'interférométrie– et difficile à cause de la complexité croissante de cette technique. Je présenterai un court état des lieux de l'interférométrie aujourd'hui. Ensuite je détaillerai les perspectives astrophysiques envisageables. Finalement je m'attacherai à évoquer quelques points spécifiques à l'instrumentation qui sont décisifs pour l'avenir de l'interférométrie.*

KEYWORDS: *Astronomy, optical interferometry, astronomical instruments*

MOTS-CLÉS : *Astronomie, interférométrie optique, instruments astronomique*

1. Introduction

When I was asked to give an invited review on the topic of the future of optical interferometry, I was tempted to give a short answer. Everybody knows where to go (see contribution of A. Quirrenbach in this volume) and there is no needs to detail these directions of developments:

– **Higher spatial resolution** meaning going from milli-arcsecond scale to micro-arcsec ones.

– **Higher flux sensitivity** meaning going beyond the Galaxy and reaching objects brighter than $K = 13$.

– **Higher astrophysical complexity** meaning going from *visibilities* to *true* images.

Therefore these advances require **many more** telescopes, **much larger** apertures, **much longer** baselines in excellent ground-based sites and eventually in space.

Will it be that easy?

We have to remind us that radio interferometry took more than 30 years from the first attempts in mid-1940's (Ryle *et al.*, 1960) to the *Very Large Array* in the mid-1970's (Thompson *et al.*, 1980). Moreover, there is a $100\,000$ ratio between the $\mathrm{H_I}$ wavelength at 21 cm and the Bracket γ line at 2.165μm and therefore a similar ratio in accuracy requirements. Interference detection in radio is done using the heterodyne technique whereas in the optical domain one has to mix first the optical signal before directly measuring it.

In addition, optical interferometry requires nanometer precision over hundreds of meters, high reliability, complex instrumental control using active control loops working at the kilo-hertz frequency, and most of all, the atmosphere is corrugating the incoming wavefront on centimeter scale on milli-second temporal scales.

Starting from the present state of the art (Sect. 2), I present the directions where one can reasonably think that optical interferometry can extend the parameter space in astrophysics (Sect. 3) depending on which instrumental issues (Sect. 4).

2. Where do we stand today?

On the hardware side, today astronomers using optical interferometry have access to baselines ranging from 10 to 350 m, aperture diameters ranging from 50 cm to 8-10 m, detection wavelength ranging from 1 to $10\ \mu$m (a few years ago even the window $0.4 - 0.8\ \mu$m was accessible at SUSI and GI2T) and space interferometry vessels have not yet been launched (SIM should be launched around 2015).

The observables accessible to general astronomical users range from squared amplitudes of the visibilities, color-differential phases, closure phases to dual phases.

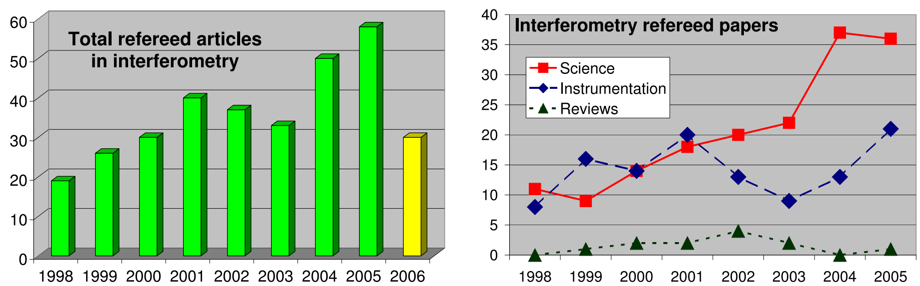

Figure 1: Refereed articles in optical interferometry (source: OLBIN). Left: evolution of number of refereed articles with years. Right: distribution of these papers between the different types of papers.

These quantities allow the astronomers to perform model fitting at different levels of complexity. Imaging has been demonstrated but it is not really a routine procedure like with radio interferometers. We are experiencing the premises of the nulling technique and narrow-angle astrometry.

Even with a rather limited scope, we have been experiencing an giant leap in the progress of optical interferometry demonstrated by the huge amount of new astrophysical results obtained during the last years (see graphs of Fig. 1 excerpted from OLBIN[1] database).

Most of the astrophysical results in optical interferometry remains in stellar physics: stellar diameters, circumstellar environments, multiple systems,... However other fields are emerging like extragalactic studies with the advent of large aperture interferometers (Swain *et al.*, 2003; Jaffe *et al.*, 2004). With increased accuracy, interferometers can measured stellar diameters of even the lowest mass stars (Ségransan *et al.*, 2003).

3. Astrophysical prospects

I do not detail here all the achievements obtained by optical interferometers in the astrophysical field since S. Ridgway in this volume already tackled this issue.

Although several orders of magnitude of spatial scales may reveal the same physics, very strong changes can occur within a simple factor 10 in spatial resolution. A good example is the case of IRC 10216 which has been observed at large scales by Mauron *et al.* (1999) with the *Hubble Space Telescope* with a field of 2 arcminutes and at spatial resolution by Weigelt *et al.* (2002) with a field of 1 arcsecond and a resolution of 50-100 milli-arcseconds. At large scales, the source appears

1. `http://olbin.jpl.nasa.gov`

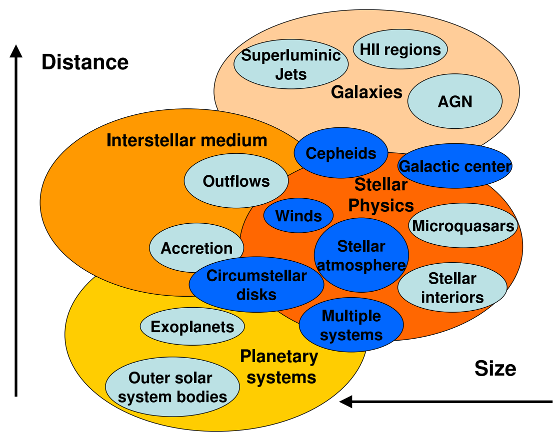

Figure 2: Parameter space for astrophysical prospects in optical interferometry. Dark colored items corresponds to fields already tackled by today interferometry. Light colored items are possible extension areas.

centrosymmetric with spherical wind whereas at high spatial resolution the source is clumpy and changes at the year scale.

3.1. *Stellar physics*

Observations with optical interferometry goes already beyond the measurement of stellar diameters with the observation of many classes of stars (young, evolved, multiple, main-sequence, massive, low-mass,...) and close phenomena like accretion, outflows, every sort of shells. Some studies of the stellar surfaces have already been achieved.

In the near future, stellar atmosphere climatology, i.e. the study of dark or hot spots, should be reachable and will provide new inputs to Doppler imaging techniques. Convection in stellar interiors should be within reach and will provide complementary evidences to those obtained with asteroseismology techniques.

Since the sensitivity of interferometers but also their performance should improve, then an exploration of the whole Hertzsprung-Russel diagram should be feasible from low-mass protostars to the remnants of stellar evolution. Similarly, the connection with interstellar medium can be contemplated by studying the influence of accretion of gas and dust material as well as reversely the consequences of the ejection of stellar matter.

In conclusion, we can imagine that the progress of optical interferometry both in the visible and the infrared wavelength ranges will open avenues to the understanding of the formation of stars and planets as well as to the comprehension of the fate of stars.

3.2. *Planetary science*

The field of planetary science will undoubtedly benefit from the progress in optical interferometry. The objects located at the outskirts of the solar system like the Trans-Neptunian Objects (TNOs) or those within the Kuiper belt are usually too small to be observed by classical techniques. Adaptive optics have shown that some of them can be spatially resolved from Earth, yet optical interferometry should be able to improve the spatial resolution of these objects.

More than 10 years ago a new field has opened up: the study of planets in extra-solar systems, also called exoplanets. Their proximity to their stellar host and the contrast of their brightness with the one of the central star make them difficult targets of observation. However, observations of protoplanetary disks which are probably the nurseries of such planets but also of the zodiacal light of these planetary systems should be possible. The formation of extrasolar systems is the occasion to observe the migration of giant planets and the planetary gaps opened by the formation of rocky planets.

Observations could be enlarge to the different types of objects so that we can explore the zoo of extrasolar planets. Interferometry might be a tool to explore the extent of habitable zone around close stars. Imaging of exo-Earth might seem a dream now but can be contemplated using interferometry techniques. A mission like DARWIN/TPF will certainly bring us clues on the status of extra terrestrial life out side the Solar System.

3.3. *Interstellar medium*

The interstellar medium has been barely examined with optical interferometry whereas it is one of the pillar of the science performed by radio interferometry. However, prospects can be imagined that will allow to observe the impacts of stellar outflows parsec away from the central jet engine traced by shocks. This is also the location of wind collision when two massive stars have strong mass loss.

By observing the dynamics of stellar clusters, either dense ones or located far away, optical interferometry can bring pieces of knowledge to the star formation and evolution. The increase in spatial resolution will allow astronomers to observe $H-II$ region in nearby galaxies.

3.4. *Extragalactic exploration*

As written above, optical interferometry has already started to observe much more distant objects like the central cores of galaxies like active galactic nuclei (AGN). In nearby galaxies, the brightest objects should be within reach: Cepheids, supernovae, massive star formation, but also fainter ones. It opens the possibility to study galaxy dynamics. This already started with the observation of the center of our Galaxy (Pott *et al.*, 2005).

Using the brightest extragalactic sources, interferometry should be able to observe the details of superluminic jets being complementary to radio Very Long Baseline Interferometry (VLBI). In addition with spectral information, very high spatial observations of super-massive black holes should also be possible. Finally one can imagine to extent the interferometry techniques to the X-ray domain.

3.5. *Top level requirements*

The requirements for optical interferometry in the current fields of astrophysics in order to increase the knowledge of these objects are **access to routine imaging**, **observe in moderate and high spectral resolution**, **increasing the spectral range** and **improve the dynamic range of observations**. To enlarge the field of investigation of interferometry toward the interstellar medium, **larger fields of view** and observations in **mid-infrared to far infrared** are required. **Higher sensitivity** and **longer baselines** are necessary to observe more distant objects like galaxies and quasars, but also to observe with enhanced spatial resolution the surface of stars. In the latter case but also in high energy physics like environments of black-holes, **access to shorter wavelengths** down to X-rays should be a priority.

4. Instrumental issues

I have listed above a list of astrophysical prospects and their translation in top level requirements. But how do these requirements have an implication into instrumental development? For example, routine imaging is necessary because modeling cannot answer all questions and imaging requires many telescopes, but how many of them? Higher spatial resolution implies long baselines but how long, or shorter wavelength but how short: ultraviolet, X-rays?

Increasing the sensitivity is a key issue, but also the contrast between the brightest object and the faintest one. Off-axis references can be used, but requires special hardware like the PRIMA facility in the VLTI. Certainly improving the capabilities a detector is also a path to follow and since the sensitivity is more or less independent of aperture size for ground-based interferometers, finding the best site is crucial. Space-based instruments should also be continued to be contemplated. However, improving single pieces of hardware is not sufficient and we must pay attention to the interferometer as a whole.

Optical interferometers are not really complicated (made of numerous elements intricately combined) but remains complex (composed of several interconnected units). For example the VLTI in the current state is made of:

– **Light collectors**: telescopes, guiding and active optics

– **Beam routing optics**: 32 motors are involved

– **Adaptive optics**: consisting in wavefront sensors, deformable mirrors, real-time controllers

– **Delay lines**: 3 translation stages, metrology, switches, control to manage carriage trajectories

– **Beam stabilizers**: variable curvature mirrors, image and pupil sensors (ARAL/IRIS), sources (LEONARDO)

– **Fringe tracker**: fringe sensor, optical path difference controller managing fringe search, group delay or phase tracking

– **Beam combination**: mainly the instruments VINCI, AMBER or MIDI which have a variety of spectral dispersion, spectral coverage, spatial filtering, detection and should control also the atmospheric dispersion and polarization

– **Control software**: 60 computers and 750,000 lines of code (Wallander *et al.*, 2004).

This is only for the combination of 2 (MIDI) or 3 (AMBER) beams! Complexity follows the power of number of apertures and therefore combining more telescopes like several tens will be a major challenge and have a high price if one does not change the type of technology used. However with increasing number of telescopes, the impact of failure is also less important than for small number of telescopes especially if the setup is redundant enough.

Calibration is an important step of present interferometry. New advances should take into account this step which becomes decisive in a good implementation plan. For examples, interferometers with very long baselines must be prepared to calibrate very low visibilities using baseline bootstrapping or other methods. Another example are spaced-based interferometers which absolutely needs to calibrate their configuration before moving to another one since it is highly improbable they can reconfigure exactly the same way. In these perspective, spectral calibration may become an interesting way of calibrating interferometric measurements on the science target itself.

In that respect, one determining question is how to combine several tens of beams: using aperture synthesis like today or should we push forward direct imaging? Aperture synthesis imaging requires less telescopes at once, that can be compensated by more observing time. This is probably the first step to imaging. Direct combination imaging is simpler to manage and more photon efficient, but requires at least a few tens of apertures and homothetic pupil combination although densified pupil technique is possible.

Other parameters should be taken into account, like the complementarity of diluted versus filled extremely large telescopes (see contribution of Quirrenbach in this volume) which is an already known story. In fact, in my opinion, this has been one the major achievements of P. Léna to succeed with his colleagues in convincing the European astronomical community to build the *Very Large Telescope* as an interferometer. We should not forget also to continue to prepare the path to space-based interferometers (see contributions of Fridlund and Ollivier in this volume).

5. Conclusion

We can conclude that there is certainly a future for optical interferometry! However it will not be as straightforward as initially and usually thought. While it is crucial to support the astrophysical use of current interferometric facilities, it is also essential to prepare the future (post-VLTI, KI, CHARA facility, ALOA), to identify which is the most suited site, to continue developing interferometry for space and of course to increase the number of apertures, the baseline length, the size of the apertures to access to even larger astrophysical topics.

Acknowledgements

I would like to warmly thanks Pierre Léna for his dedication and his commitments to the development of optical interferometry in Europe. On a more personal side, I would like to thank Pierre who have introduced me into interferometry and has been and still is an example to follow.

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